SAND2023-13127

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Sandia National Laboratories

Combinatoric Researchers at Sandia National Laboratories: An ethnographic study

Jessica G. Turnley, Diana L. Bull, Jeffrey Y. Tsao, Peter M. Gambill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Combinatorial research, the incorporation of multiple domains in a unified research agenda, is a strong contributor to the growing corpus of scientific knowledge and technological advancements worldwide. In 2019, a study team at Sandia National Laboratories (Sandia, the Labs) used a systems approach to understand if and how combinatorial research agendas were playing out at Sandia, one of America's premiere national security research venues. The study team used the data collection effort described in this report to ground the discussion of the broad social environment and particular organizational environments within which combinatorial research agendas are developed, as described in the full study. The team interviewed twenty-five staff members engaged in combinatorial research at Sandia in New Mexico and California during the months of June – September 2019. Analysis of this corpus of ethnographic data, combined with knowledge drawn from relevant literature, concluded that there is an individual type who would be most likely to engage in combinatoric research, described by both demographic and psychographic components. This type demonstrates both intellectual depth and the curiosity which leads to breadth. The analysis also showed that Sandia as an organization and as perceived by the respondents, set up tension for the combinatorial researcher. While Sandia was generally agnostic towards combinatorial research, that agnostic posture depended on whether the researcher was able to fulfill all her customer obligations – obligations that are structured primarily in transactional relationships with customers with relatively short time horizons. This report concludes with suggestions for additional research in the ethnographic domain.

ACKNOWLEDGEMENTS

The study team would like to thank the Sandia researchers who gave their time for the interviews that form the basis of this report.

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EXECUTIVE SUMMARY

Combinatorial research, the incorporation of multiple domains in a unified research agenda, is a strong contributor to the growing corpus of scientific knowledge and technological advancements worldwide. In 2019, this study used a systems approach to understand if and how combinatorial research agendas were playing out in one of America's premiere national security research venues, Sandia National Laboratories (Sandia, the Labs). The team decomposed the research system into three parts: a macro-level description of the American research environment, a meso-level dissection of a particular organization embedded in that environment, and a report at the micro (ethnographic) level of the experiences of combinatorial researchers in that environment. Evidence of the experiences of Sandia researchers was collected through a set of twenty-five interviews with staff members engaged in combinatorial research in support of the third level. This document reports on that data collection effort and the subsequent analysis of the comments provided by the respondents.

The document begins by describing the research method. It includes a discussion of the sample selection logic, and a brief description of grounded theory (Glaser and Strauss, 2017 [1999]), an analysis method which allows categories of significance to emerge from the data. The results of the data collection process begin with a presentation of the demographics of the sample and the significance of that demographic picture. The data are then presented in a structure of categories that emerged through the analysis process, beginning with various aspects of working combinatorially that were expressed across the sample, moving to a description of the researchers, how respondents team, and finally how Sandia influences their pursuit of combinatorial research.

For the respondents' complex problems, foresight, and analogic thinking drove the cross-domain approaches found in combinatorial research. The growing corpus of knowledge used to address complex problems is becoming ever more accessible to the individual researcher with the desktop (fingertip) presence of sophisticated search engines, various mechanisms of information push such as listserv, and the increasing number of black box algorithms that make it easier for an individual researcher to cross domains. The rise of serendipitous exposure to a variety of domains through these technological advancements was central to developing combinatorial research agendas for the respondents.

A combinatorial capacity allows researchers to be breadth-seeking while also demonstrating the ability to work well in a deep disciplinary environment. Breadth-seeking, combinatorial research requires certain interpersonal capabilities, such as some measure of extroversion and agreeableness, in order to work successfully on cross-domain teams. Combinatorial researchers also need to be able to engage in curiosity-driven exploration that benefits from an openness to new experiences. This configuration has been described as a T-shaped employee, a characterization that was generally confirmed by the respondents.

Respondents were comfortable with discomfort, open enough to other individuals to establish weak social/intellectual ties that could yield team members and exhibited a high level of curiosity about the world. That said, many of them looked to Sandia first (and sometimes exclusively) for collaborators. That avoided many of the challenges associated with navigating external collaborations in Sandia's secure and compartmented knowledge environment.

Respondents found Sandia to be agnostic to combinatorial research. Skills-based hiring practices that favor deep domain knowledge and time reporting requirements that limit curiosity driven exploration were the two most frequently mentioned organizational dynamics underlying combinatorial research. So long as a researcher was able to be fully funded and to execute against those projects, she was able to investigate domains new to her that might generate combinatorial research ideas and agendas. Therefore, much of the exploratory work and learning took place on a researcher's own time – evenings and weekends. Respondents further mitigated their career risk by waiting until they had established a strong reputation in their core domain before turning to combinatorial efforts.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CEO	Chief Executive Officer
LDRD	Laboratory-Directed Research and Development
R&D	research and development
ROI	return on investment
Sandia, the Labs	Sandia National Laboratories
STEM	science, technology, engineering, and math

1. INTRODUCTION

Combinatorial research, the incorporation of multiple domains in a unified research agenda, is a strong contributor to the growing corpus of scientific knowledge and technological advancements worldwide. In 2019, a study team from the Systems Analysis center at Sandia National Laboratories (Sandia, the Labs) used a systems approach to understand if and how combinatorial research agendas were playing out in one of America's premiere national security research venues, Sandia National Laboratories. The team decomposed the research system into three parts: a macro-level description of the American research environment, a meso-level dissection of a particular organization embedded in that environment, and a report at the micro (ethnographic) level of the experiences of combinatorial researchers in that environment. Evidence of the experiences of Sandia researchers was collected through a set of twenty-five interviews with staff members engaged in combinatorial research.

This document reports on that data collection effort and the subsequent analysis of the comments provided by the researchers.[1] The first section of this document describes the research method, including the sample selection logic; a brief description of grounded theory (Glaser and Strauss, 2017 [1999]), which structured the analysis; and an overview of the analysis process that the study team followed. The next section provides the results of the data collection process. In accordance with the grounded theory approach, participant comments are organized by the categories that emerged from the raw data, rather than by *ex ante* categories imposed upon the data by the analysts. The discussion section briefly describes the picture of a combinatorial researcher at Sandia as constructed from the interview data. The concluding section summarizes the results of this ethnographic analysis in terms of the larger study on combinatorial innovation.

[1] This report is designed as supporting data and analysis for the full report on combinatorial innovation (Bull et al, 2020).

2. METHODOLOGY

The study team used this data collection effort to ground the discussion of the broad social environment and particular organizational environments within which combinatorial research agendas are developed. (Discussion of the social environment and the organizational environment can be found in the full study report.) The team interviewed twenty-five staff members engaged in combinatorial research at Sandia in New Mexico and California during the months of June – September 2019. Sandia is a Department of Energy multi-program laboratory with an annual budget of $3.6 billion in fiscal year 2018 (FY2018). Sandia has 11,500 employees, of which approximately 7,000 are classified as Research and Development/Science and Engineering staff, i.e., holding a job involving research and development.

2.1. Sample Selection

There is no central point at Sandia at which the research agendas of all staff may be viewed and from which a sample for this study could be constructed. Hence the study team decided to use a snowball sample: study team members would identify a few potential respondents who were known to them as practitioners of combinatorial agendas and ask each of the respondents for additional names.

Although the study team's target population was potentially large, it was made operationally accessible by professional networks that exist among the technical (research) staff at Sandia. Some staff, now retirement-eligible, have served over three decades at Sandia, with many holding positions in a wide variety of technical areas. This professional longevity and organizational and programmatic movement allowed them to create networks across many elements of the Labs. Their professional networks thus became mutually intertwined in many ways. The group at Sandia that sponsored this research had recently conducted efforts under another project to elicit information from across Sandia in pursuit of senior leadership strategic efforts, creating their own networks throughout the Labs in the process. Finally, the study team for this research had members who were immersed in both these staff- and group-created networks, and who had their own professional networks across the Labs.

Using these perspectives as an initiation point, the study team created the beginning of a snowball sample. A question at the end of each interview elicited names of people the respondent felt fit the study team's profile of a combinatorial thinker, based on the picture that emerged through the interview. As the snowball sample grew, a mid-course look suggested that the list was weighted in favor of mid- to late-career respondents. The study team then began asking both for names of combinatorial thinkers at the Labs and, specifically, for early-career combinatorial thinkers. As the sample size approached twenty-five, respondents began to provide names of individuals we had already interviewed. At this point, the distribution of the respondents across the Labs' organization and areas of work, coupled with knowledge of members of the study team who had high-level engagement with these types of researchers, suggested that the sample was reasonably representative. Resource (time and funding) constraints also precluded additional interviews.

Once a potential respondent was identified, recruitment was accomplished through an email from a Level 2 manager. (As all respondents were at the staff level, the email would have come from the respondent's skip-level manager.) A time-charging number was offered for the respondent's time, but no other type of compensation was offered. All respondents accepted.

2.2. Conducting the Interviews

All interviews at the New Mexico site were conducted in person. Interviews with respondents based at the California site were conducted either by phone or in person if the respondent was in New Mexico for other reasons.

Each interview was conducted by a team of two: an interviewer and a note taker. The interviewer was the same for all twenty-five interviews: a cultural anthropologist trained in qualitative data elicitation and analysis, with over thirty years of experience working with Sandia. The note takers rotated among three other members of the team. Assignment of the note takers was based on availability, with an effort to roughly divide the work among the three. The interviewer also took her own notes.

Due to the restricted nature of the sites where many of the interviews were conducted, recording materials were not allowed so transcriptions of conversations were not an option. None of the note takers were trained in dictation or any other method of direct conversation capture. However, note takers were often able to capture key phrases in the respondents' own words. This method does mean that many interview notes are not verbatim: they are the note takers' interpretation of the respondents' words. While this is a limitation of the results, the study team believed that it captured sufficient verbatim text to use as a basis for analysis.

The interviews were conducted as semi-structured interviews, guided by a protocol. Appendix A provides the protocol. The protocol was designed to identify areas of interest to the study team and ensure that they were covered in each interview, while allowing flexibility for the respondent to take the conversation in directions unforeseen by the team.

2.3. The Analytic Approach

All team members participated in the analysis of the results. The analysis was structured by a grounded theory approach (Glaser and Strauss, 2017 [1999]) in which the analyst(s) codes the data and looks for themes or patterns that emerge from the data, rather than imposing predetermined categories on the data. While the study team recognized that the protocol did somewhat constrain responses, the open-ended, semi-structured nature of the interviews allowed unexpected responses to emerge, so the protocol questions alone were not sufficient for categorization.

One of the major charges against qualitative data analyses using coding schemes is that assignment of a datum to a category is highly analyst-dependent. To mitigate this concern, the study team conducted the analysis in several phases with different analysts coding the same data.

For the first phase of analysis, all four members of the study team read through all the interview notes and, through discussion, created a rough set of categories. In phase two, the interviews were divided so the interview notes of each respondent were assigned to two analysts, with the number of respondents carried by each analyst roughly equal. The analysts re-read the interviews and coded data to the categories collectively identified in the first phase. During this task, assignment to a Miscellaneous category was possible, as was development of new categories if an analyst saw one emerging from the data.

In phase three, the team reconvened and restructured the categories, based on the data coding in phase two. Some categories were lost, others combined, and some new ones added.

In phase four, assignments of respondents to analysts were switched, and the data re-coded. Subsequent discussion indicated that the revamped categories seemed to generally hold.

As a final check on the categories, in phase five the assignment of respondents to analysts was switched around once again, with a final look at the data.

Although the coding exercises dealt with "chunks" of data from the interviews (a sentence or a phrase would be a chunk or a datum), the team recognized there is an interpretive aspect to qualitative information elicited from human respondents that depends on delivery by the respondent and context. The tone of the interview matters, and that is often not captured in small data chunks. The social context of the respondent also matters (her[2] social location in the organization and in her professional world), which is another dimension that is not caught in a set of words. Plus, words can mean different things to different people, with definitions clarified in conversation by context. Again, this variability is lost in the chunks of text that serve as data. These concerns were somewhat mitigated by the data elicitation method. The interviewer was present at every interview and so could speak to differences in these qualitative aspects. The presence of a second team member (the note taker) helped refute or validate the interviewer's observations. Differences in perception were resolved by a conversation between the two team members present at the interview.

[2] Our respondent pool included both males and females. However, gender/sex did not appear as a discriminating factor in the interview results. Therefore, for editorial ease, we will use the feminine pronouns throughout.

3. RESULTS AND ANALYSIS OF DATA

The first result, and one that describes an important dimension of the context of the elicited data, is the sample itself. The first part of this section describes the demographics of the snowball sample as it appeared at the completion of the twenty-five interviews.

The analyses following the sample description are the end product of the methodology described in the previous section. The data is presented in terms of the categories that emerged through the analysis process, beginning with various aspects of working combinatorially that were expressed across the sample. These work descriptors suggested there are some personality types that do better at combinatorics work than others. While this research was not explicitly directed at psychological types, a picture began to emerge from the data.

Next is a discussion of the people who conduct this type of work, which draws on the self-descriptions of the respondents, including their preferred or "clone" hires. This section also describes how the respondents connect with others (social networks). A section on characteristics and workings of the teams created by exercising these networks follows.

The final results section provides the respondents' perspectives on both the organizational environment and also the constraints and opportunities offered by Sandia for combinatorial work.

Note: Any text in double quotation marks represents verbatim responses captured during the interviews.

3.1. Demographics of the Sample

The study team expected to see a bias in favor of early-career respondents as the snowball sample gained momentum since that cohort would have come of professional age when combinatorial innovation was in ascendency. For purposes of this study, early-career was defined as less than ten years of professional work. Mid-career respondents had ten to twenty years of professional work, and late-career more than twenty. Mid-course, the study team observed that the demographics of the sample up to that point showed a distinct bias in favor of mid- to late-career respondents, so the interviewer began asking specifically for names of early-career staff. Despite that request, the completed sample of twenty-five respondents displays a distinct bias in favor of mid- to late-career respondents—in fact, late-career respondents comprised close to half (40%) of the sample (Figure 1).

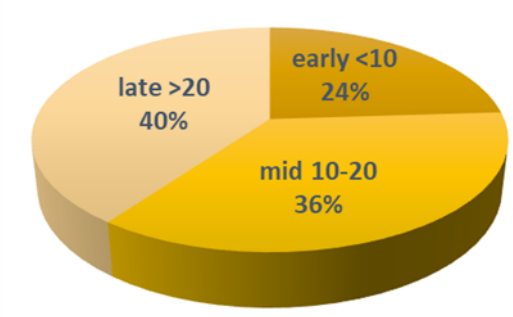

Figure 1. Career Position of Respondents (In Years)

The study team did not control for gender. Not surprisingly, the sample reflects an expected bias in favor of males as this research was conducted with a science, technology, engineering, and math (STEM) workforce, many of whom had decades on roll (Figure 2). However, the analysis process indicated there was no significant difference between responses from females and males.

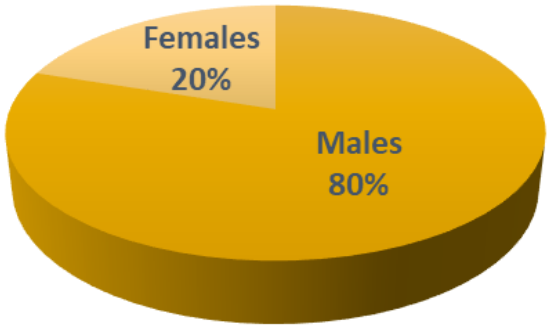

Figure 2. Respondents by Gender

Sandia has about 11,000 employees working at its Albuquerque, New Mexico campus, and just under 1,000 at its Livermore, California campus. There are significantly different valuations of certain behaviors at the two sites, driven both by the differences in size and the location of the California campus near but not in Silicon Valley. As this was a snowball sample, the study did not control for work location, other than to ensure that there was some representation from the California site in the sample. Although the final set over-sampled California (which may itself be of significance) (see Figure 3), there was no significant difference in responses from respondents at the two sites.

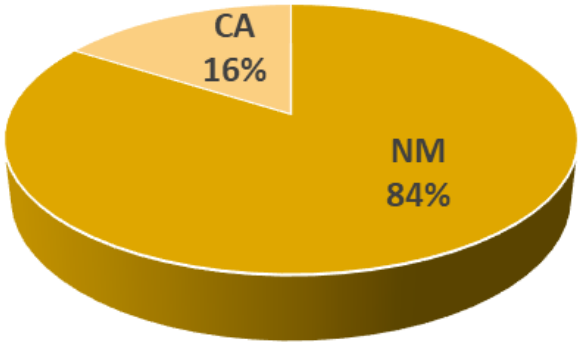

Figure 3. Respondents by Location

As a multi-program laboratory, Sandia provides scientific expertise in a wide range of disciplines and application areas. The sample reflects this diversity in the current specialties of the respondents (see Table 1). Note that the current specialty of the respondents often was significantly different than the area in which they received their advanced degree(s).

Table 1. Current Specialty of Respondents

Artificial intelligence and complex systems	Materials chemist (inorganic)
Chemical and materials sciences	Materials chemistry
Computational neuroscience	Materials science, electrical engineering, and physics
Computational science/cyber security	Mechanical behavior and materials
Computer science	Metrology
Data analytics	Nano-biologist
Data analytics/machine learning	Photonics
Electrochemical sensors (microneedles)	Physics
Electro-magnetics	Power systems / radiation hardened
Electronic structure calculations (chemistry/physics)	Robotics and control systems
Energy science and technology / solar	Statistical inference
Inorganic chemistry	Synthetic biology

3.2. Working Combinatorially

This section uses the categories that emerged from the analysis of the data to describe how respondents exercised combinatorial research agendas, including such factors as balance between breadth and depth in their work, their motivation to engage in it, what they perceive as their return on their investment (ROI), and how they re-characterize failures as important learning opportunities.

3.2.1. Depth of Combination

Respondents identified two ways in which domains[3] could be merged: a "willingness to go deep" into a second or third domain to truly fuse the knowledge or technology bases or staying very broad at a high level to "put pieces together." Ten of the twenty-five respondents addressed the need to have deep underpinnings of understanding if one was to be successful in bringing together multiple domains, to "advance knowledge deeply." However, these same respondents simultaneously acknowledged that "you can't do first principles thinking on everything" because it requires "time, effort, and thinking." Another, and sometimes overlapping, group of nine respondents acknowledged that "proof of principle was enough" to understand how to bring domains together

[3] To avoid any affiliation with science or technology, or arguments over where the borders of a particular discipline are drawn, the authors have chosen the more generic term "domain".

without "becom[ing] the world's expert at that thing." Yet another solved the breadth/depth problem by "fund[ing] people to just come in and sit in on my meetings […] especially senior people who can kibbutz and force us to re-explain things so that we can get out of our heads."

3.2.2. Problem Identification

Often, but not always, self- or other-identified problems such as inconsistencies, needs, and time and effort minimizers motivated this group of researchers to find solutions in technologies, processes, calculations, and the like. The process of identifying and defining the problem for these researchers was founded in active listening, open questioning, and often iterative probing. One respondent noted both the role of serendipity and the importance of engagement through a wide variety of media and topics with the comment that inspiration is "always related to things you read in the last week."

Nine of twenty-five respondents noted the importance of "finding out what customers really need and trying to solve" it. The importance of "adapting to meet the asks" or "starting with customers and needs" in mind played a major role for this set of respondents.

For another nine respondents, problem identification was more of a personal or team-initiated process in which observations of something that could be improved in the world formed the stimulus for the research. As one respondent noted, "you need to get sparks started; this doesn't happen sitting in the office. Getting out and seeing other things is key." Going to conferences, talking with colleagues, reading widely, and paying attention to the world were all cited by several respondents as important avenues to initiate these "sparks."

Eleven respondents, or nearly half of the respondent pool cited foresight as a main driver in the problem-solution pairing. "When I look at what people are doing, I try to think ahead—what are the next couple of problems they will encounter?"

3.2.3. Drivers of Cross-Domain Approaches

Clearly not all problems require a cross-domain approach. However, this research specifically targeted respondents believed to be pursuing cross-domain work. All twenty-five respondents confirmed that they use cross-domain approaches in their work (validating the sample). One respondent went so far as to say that "interdisciplinary is moving to continuous discipline" to identify the importance of including other domains in solution finding.

Five of the respondents suggested that a primary driver of cross-domain solutions lies in the complexity of the problems being addressed. "The complexity of problems that people are working on is increasing. The number of parameters is exponentially increasing." Another respondent pointed out that "Today [there is] a much more interdisciplinary approach, [it is] not a single investigator. [You] need different backgrounds." Interestingly, one of the highly technical researchers noted that her team is including "economics and politics into our field of view in order to gain a more complete understanding of what's driving trends" that will influence the direction of her research.

Six respondents also noted how changing a frame of reference to redefine a problem to one that was solvable was the key insight that led to an intellectually profitable research agenda. Analogic thinking, an often-used method to change frame of reference, requires the scientist to look at other domains. As one respondent said, "Coming at the same topic from two very different points of view is so powerful." Another confirmed "[I am] more creative when using analogic thinking." But as the first noted "This is hard," intimating at the need for teamwork. Lastly, five respondents identified

that cross-domain work was specifically requested in various calls for proposals, leaving them little choice in the matter—and suggesting that the necessity for cross-domain research is recognized in the funding/customer community as well as in the research community.

3.2.4. Incentives for Pursing Cross-Domain Approaches

Respondents identified several incentives for pursuing cross-domain solutions. The previous section ended by describing a structural incentive, i.e., calls for proposals that specifically required demonstrations of cross-domain work. Other types of incentives discussed by participants lay in the intellectual thrill of acquiring a new perspective on a problem or solution space, and the contribution of cross-domain approaches to increases in various types of impact.

The unexpectedness associated with cross-domain thinking was identified by twenty out of twenty-five respondents as an incentive because "novelty is where it isn't evident": by bringing in "orthogonal approaches" one is able to expand the space of the possible. Twelve of the twenty respondents who mentioned the role of the unexpected also specifically identified the importance of surprise.

According to respondents, cross-domain approaches can be a mechanism to increase attention to one's work by the funding community. For example, after trying for multiple years to get funding for a particular methodological approach to a problem, one respondent was able to get funding only by "giving them a [related but] ridiculous idea" that incorporated another domain in an unexpected fashion. Cross-domain approaches also give an advantage to the proposer because the introduction of an unexpected domain raises the possibility that "they [funding body, customer, public] don't know what is counter-intuitive and what isn't." So not only can a cross-domain construct become more memorable than a single domain construct, it can also benefit the proposer because the potential lack of deep knowledge of the second domain on the part of the funder or other proposers means that a deep evaluation of the proposal is not possible. Four respondents also noted that by working in the "gaps" between domains, competitiveness is decreased without a loss in value. There is "just as much value in the parts where others are unwilling to stretch themselves." These "gaps" are really just places that are "reasonably well defined but [with] enough space to make insights." Eleven, or nearly half of the twenty-five respondents, noted that employing cross-domain approaches was advantageous because there is "nothing to lose but everything to gain [because there are] no assumptions going in and no prior agendas."

The respondents in the study acknowledged multiple dimensions of the ROI in cross-domain approaches. Some specifically call out traditional ROI features ("distributed approaches will yield a higher impact for lower cost") while others focused more on the impact ("when [I] do publish or attend conferences [I] see higher impact").

3.2.5. Funding

Funding streams and the ways in which funding can constrain or incentivize research direction played an important role in how the respondents pursued combinatorics research, and so it is addressed here. Funding will be addressed again in the section on the influence of the organizational environment.

Seventeen, or two-thirds of the respondents, talked about the various roles that funding plays in generation or pursuit of a combinatorial research agenda. To really pursue any research agenda, they noted that "ideas have to be connected to money" and that sometimes morphing a research concept to fit funding calls was necessary. Further, time—which equates to funding under a full-cost

recovery business model—is needed to learn about and incorporate other domains. As one respondent noted "you don't always have money to change direction right away." Several respondents noted that there was little time (and hence funding) to learn new things and, therefore, this type of learning was mainly done on their own time. This last dimension of the funding problem will be addressed later in the section about the influence of the organization.

Funding is allocated to the Labs based on project needs. One of the respondents pointed out that to "be successful as a researcher at Sandia, you have to be deep because deep is what brings in the dollars" implying that the breadth of field required by combinatoric research agendas does not fit well with Sandia's customer base and its needs. Hence, there is an immediate tension between the desire of those who want to do cross-domain work and what they are actually funded to do. This tension was not pervasive across the respondent pool, but it was noted in several interviews.

Another important aspect of funding relates to the cost structure of Sandia, which may preclude the inclusion of researchers from other institutions who can provide insight into domains that Sandians cannot. As one respondent noted, "Our cost structure makes it unfeasible for Sandia to participate on collaborative research projects with universities, as staff rates are five times those of the university staff."

3.2.6. How Combinatoric Researchers Learn

Respondents pointed out that there is a large amount of material now available to researchers as a result of technology-based innovations in knowledge access. One commented that "there is so much more information available [than there had been in the past]." It was noted by nine respondents that online querying techniques (such as Google (www.google.com), SciFinder (www.scifinder.cas.org), and YouTube (www.youtube.com)) provided relatively easy access to a lot of knowledge. Machine learning, data analytics, and automated research notifications were mentioned by two respondents as areas in which technology advances were allowing better utilization of the accumulated corpus of knowledge across many domains. As one respondent put it, "[there's] not just a lot of data out there, but [one] can get to it effectively." One respondent even pointed out that the field of computer science moves so fast that relying on "blog posts or forums - not even papers" was the most reliable way to get up to date information because, as another respondent noted, "by the time materials are cleared for journal publication the concepts are relatively well known."

Nine respondents gave feedback on how they achieved a depth versus breadth balance, which ranged from going to conferences ("I've been going to cross-fertilization conferences. Small professional societies. It is good to not present and just have discussions.") to "brainstorming questions in response to proposal calls" to reading ("I typically search for primers on new topics and work through them. As I do, I focus on information essential to understanding a topic area to build a scaffolding or skeleton of principles").

Technological advances also are beginning to relieve the tension between an individual's learning rate and capacity, and the corpus of knowledge available. As one respondent pointed out, "[you needed] theorists who would perform quantum calculations [in the past], but today you can buy programs that allow you to make these calculations without being a theorist." Another noted that advances like word2vec (Mikolov et al., 2013a; Mikolov et al., 2013b) in the machine learning and data mining domains "allows materials discoveries for one application with significant probability of being used in another application."

According to respondents, increased ease of access to a large knowledge base has increased serendipitous learning. As one respondent said, "Luck is a big factor—what have you recently been seeing? That is how you become aware of how to combine two ideas." Respondents said that they are "reading a lot of random things." They are able to "browse a wider net" for "the really new ideas." For some, the problem becomes one not of access but of filtering. "There is too much to draw on, it's hard to know how to narrow down."

The ability and the interest to engage in analogic thinking played a part in the respondents' ability to incorporate material from multiple domains. Five respondents explicitly noted the importance of analogic thinking. As one respondent commented, "I will bring in an orthogonal approach to improve (the resolution –) quality of the research."

Despite many comments on the importance of technology for knowledge access, when queried directly on their own methods of knowledge access and learning, respondents provided responses that relied rather heavily on interpersonal interaction. Thirteen, or about half of the respondents, lauded the importance of conferences for learning about new areas in particular, as "learning from people is way faster than learning from textbooks." Conferences also serve as a filtering mechanism for respondents as they engaged with a new domain. "Conferences are essential for me to figure out what's important to learn." Nineteen of the twenty-five respondents, or three-quarters of the sample, said that reliance on interactions with experts in the domain to clarify concepts was also important.

Reading was extremely important to most of the respondents (eighteen of the respondents or almost three-quarters of the sample). Examples they provided of reading materials included abstracts, journals, books, newspapers, magazines, and calls for research from different funding bodies. Circulation via email with colleagues of items that could be of interest, interactions with mentors, and conversations that arise from meetings all appeared as additional learning mechanisms.

Five of the respondents specifically mentioned more formal mechanisms like classes or online training mechanisms. Lastly, in addition to conferences, reading, personal interactions, and classes, two respondents mentioned "experiential and practical" learning as extremely important, believing that craft is a real and important aspect of truly acquiring knowledge in a domain (a commonly noted mechanism).

Respondents described environmental factors that influence the amount that they can learn, particularly because learning "is just hard work." "You have to dedicate time to find funding to expand your views," said another. Others spoke of the personal cost in terms of work/life balance as they had to explore new domains on their own time. "Compromises in private life are required," said one. "I come in over the weekend. The problem there is that there's little time for the rest of life," said another.

3.2.7. Risk

Fourteen of the seventeen respondents who talked about risk in the interviews (80% of that sub-sample, which is just over half of the total sample) viewed the risk of pursuing combinatorial agendas as an intellectual risk. (There were a few comments related to institutional risk: these will be addressed in a later section.) For example, one said that "It's not as if I'm looking for risk. It's just something I accept as a consequence of doing something new." Another specifically noted that "cross-disciplinary work is riskier because it is more difficult to know whether you're going astray because you just don't know enough. A gotcha that you didn't know because it's not your field."

The comments about high levels of risk in the pursuit of combinatorial agendas should imply high levels of failure. However, fifteen of the respondents, or about two-thirds of them, reframed a question about the high risk and associated high failure rates of combinatorial research agendas into a demonstration of scientific progress. "Mistakes can be turned to advantage," said one. "Being open-minded to new goals, not to mention learning, means that you really don't fail." Another said that "[It is] never totally a failure. Things you learn come back to help you." "Science is mostly about failure," one of the respondents pointed out. "That's how you learn." Yet another said that "you have to fail to learn."

3.3. Who Are These People?

The previous section, which described how respondents worked combinatorially, made references to personality dimensions that enabled—or, in fact, may have encouraged—the respondents to do so. This section addresses those dimensions. While these interviews were not an instrument directly constructed to elicit psychological or personality-based information,[4] the study team believes that the interviews raised some interesting points regarding the type of persons to whom combinatorial research would appeal.

3.3.1. Personal Characteristics

Respondents were asked, "What would we look for if we wanted to hire someone like you?" and/or "What allows you to do this [interdisciplinary work]?" Twenty-four respondents, or just one short of the total, had some positive comment related to the importance of intellectual openness: breadth-seeking, curiosity-driven, and comfort with discomfort.

Thirteen of the respondents described themselves in some way as being comfortable with some level of intellectual discomfort—of being willing to move out of their comfort zone. Given the context of this study, this concept most frequently was phrased as a willingness to be a neophyte in a field of study other than their own. "I am willing to go outside my comfort zone," said one. "I'm OK to jump into areas that I'm unfamiliar with." Another said that "you have to not be afraid of areas you know nothing about." A few phrased these behaviors explicitly in terms of (intellectual) risk-accepting behaviors. "Intellectual risk-taking is important…you have to be not afraid to go into unexplored territory." One respondent paired intellectual openness with humility: "Be willing to delve into areas you don't know anything about…but also be humble enough to recognize that you know so little that you can't work there," one respondent said.

Five of the respondents used words/phrases that directly spoke to intellectual and professional openness such as "open to learning," "open to hearing new ideas," and the opportunity cross-disciplinary work afforded to "reinvent yourself." In the same vein, an additional nine respondents used descriptors such as "boundary-crossing" and "always looking for new opportunities." Yet another characterized herself as "mentally attuned to changing fields" and described her "most satisfying accomplishment: doing things different from what she was trained." A set of thirteen respondents spoke in some way of being "curiosity driven," again reflecting the importance of being open. "Curiosity is super important," said one. Another described it as opportunism. "I'm an incredibly opportunistic person," she said.

[4] The study team hopes that the suggestive points in this section and elsewhere in this document would be a useful starting point for a psychometric study of individuals engaging in combinatorial research agendas.

Eleven respondents (slightly less than half) gave responses to the hire/clone questions that were binned in the category labeled as depth-seeking per the analysis exercises. One said that "I think I have more impact if I stay in my discipline," where follow-on questions determine that for her, impact is measured by publications, keynote speaker invites, and similar metrics. Notably, of those eleven, all also gave responses that fit the previous set of categories corresponding to openness. Explicitly linking the two, in response to a question about what enabled her to go broad, one respondent replied, "My willingness to go deep. You have to be able to go deep, otherwise you're just bringing together things that you don't understand."

Continuing the conversation about the importance of domain depth, one respondent pointed out that "doing one's homework is important. You have to put in the time, the effort, the thinking. Nothing substitutes for that." "I'm not that agile because there is a cost to being agile," said another respondent. "It's taken a lot of time and effort to learn the methodology that I know."

Interestingly, the responses to the hire/clone questions as well as responses elsewhere in the interviews contained very few mentions of the importance of intelligence (only four respondents directly mentioned it in response to the hire/clone question). Almost all the questions had more to do with personality characteristics than with intelligence, or, as in the case with eleven respondents, the importance of an ability to function well in a team environment.

3.3.2. Importance of Prior Personal Achievement

Respondents noted the importance of prior personal achievement in positioning them for cross-domain or combinatorial work. It is important here to keep in mind that all respondents queried during the effort to build the snowball sample had a difficult time providing names of early career individuals at Sandia who also were successful in interdisciplinary work.

Of the eleven respondents who spoke explicitly of the importance of their reputation external to Sandia, eight, or about a third of all respondents, mentioned the importance of establishing a research reputation, which usually requires publishing in their core area (i.e., having a significant presence in their primary technical discipline). That reputation allows them to obtain funding for their current interdisciplinary work ("I had six years as…a professor where I built a research reputation, and I've been able to use that reputation to get support for current work.") and contributes to Sandia's ability to hire top talent, which could contribute both to disciplinary and interdisciplinary approaches. One respondent emphatically said that "Your ability to attract (new talent) is proportional to your reputation for good work—publications and conferences." Only one respondent believed she will not establish a solid research presence through her work at Sandia that drew on many different disciplines. "I have come to the realization that I won't receive the level of recognition here [at Sandia] that I would in industry. Cutting edge research requires one to be focused on one area of expertise [and I am not]." However, this individual was late career at the time she was interviewed and had a strong career in industry behind her.

Seven respondents directly commented that being established in their careers helped them to adopt or work with an interdisciplinary approach. Three respondents said that their established track record gave them a space to act in ways that otherwise might have been discouraged. One of those respondents put it this way: "I've been successful and so do have the privilege to be productively confused and to take risks."

In some cases, mid- and late-career respondents felt they had the benefit of greater immersion in problem spaces that might stimulate an interdisciplinary approach. "I have been exposed to a lot more problems," said one. Another felt that her experience allowed her knowledge of funding sources and gave her a reputation to work on problems she might otherwise have not been able to investigate: "I got hooked into several projects on which I impressed people, which meant I then had somewhere to go to get money to carry forward my new innovative ideas."

Only five offered comments that spoke to the importance of a reputation internal to Sandia. Those comments generally related to the ability to use Sandia internal resources—an ability acquired through experience and the development of a reputation and credibility. The resources included people tapped through networking contacts, internal funding, or other resources that require political knowledge or knowledge of how to "work the system."

3.3.3. Passion

Eleven of the respondents communicated in the tone of their responses what the analysts interpreted as a passion for the interdisciplinary work they pursued. Seven pointed out that they pursued this type of intellectual exploration outside of work hours. "For my passion projects I work a lot of overtime. I come in over the weekend," said one. Others spoke of the importance of being "self-motivated," to be willing to pay the various costs (such as out-of-work time, uncomfortable feelings as a neophyte) involved with the pursuit of these new areas.

3.3.4. Balancing Breadth and Depth

Some of the earlier sections in this discussion alluded to the need of combinatorial researchers to balance intellectual depth and breadth.

Sixteen of the respondents gave positive comments about the need to address and/or achieve this balance. Many expressed their endorsement through examples. Others responded directly to questions about the balance. When asked if there was a research risk if one did not employ interdisciplinary approaches, one respondent replied, "Yes. The risk is that I'll go off and exhaust the limits to my own methodology. I need to be exploring more broadly other methodologies," speaking to the importance of both breadth and depth. Another spoke directly to the danger of upsetting the balance. "If you bear down too much in one's area it can limit innovation. Every idea has been thought of, but so what. You need to get over [that] hump. If one is so immersed in their wealth of information, sometimes they have a hard time figuring out how to get over [the] hump." Yet another illustrated how she used both interdisciplinary and disciplinary approaches. "They are getting a different perspective on problems outside of their expertise…I have become a jack of all trades…and then I have people with domain knowledge that can use a spark to go somewhere."

Thirteen respondents spoke of the cons of failing to achieve a such a balance—of being either too interdisciplinary or too deeply disciplinary. Nine of these thirteen also spoke of the pros of the balance, suggesting that they were aware of the pull or tension between depth and breadth. Some spoke directly to the balancing act necessary between depth and breadth, answering in the emphatic affirmative when asked if there is a tension between having a disciplinary presence and being interdisciplinary. Recall the previous comment from a respondent where she explicitly said that her "willingness to go deep" was what enabled her to be broad. Another put it a little more bleakly, referencing the cost to one's reputation: "The risk is that if you spend all the time making connections you aren't doing work to make yourself relevant" where context showed that "relevant" meant establishing a reputation in the researcher's core discipline. The comment from another

respondent put it directly: "Cutting edge research requires one to be focused on one area of expertise." Another put the difficulties encountered with interdisciplinary work in Sandia-specific terms: "Your typical disciplinary Sandia researcher can't do this. They have a vested interest and passion in their discipline that biases them to want to stay in their discipline. Indeed, to be successful as a researcher at Sandia you have to be deep, because deep is what brings in dollars." (The influence of the organizational environment is treated in another section.)

Only six respondents made comments that could describe their personal motivation to move from a position of depth to one of a balance between depth and breadth. Motivations ranged from the opportunistic, "no one else was doing it so I jumped in," to the personal, "I want to be creative" and "[I] want to have impact."

3.3.5. How Are They Connected? Importance of Networks

The interviewer asked if and how collaborations were pursued in combinatorial research, and the respondents were quite clear about the importance of the social component of combinatorial innovation. All twenty-five respondents made some comment relating to their connection to others. While this may not be extraordinary on the surface, it does point out that combinatorial innovation usually is a social phenomenon. It is not the result of a researcher working alone in the lab, but of a researcher embedded in certain types of social relationships.

Some of the respondents spoke directly of the importance of networks. Five respondents were explicit about the need to have "good" networks. "Knowing the right people is critical," said one. "I do it [find people for my teams] completely through my own networks and contacts." One other respondent pointed out that out of the approximately 200 papers she has authored, on only one was she the sole author.

Conferences seemed to be a good place to initiate and maintain weak ties.[5] Fourteen of the respondents mentioned that they used conferences as a way to get ideas. While the interviewer did not explicitly ask whether they only listened to presentations at the conferences or engaged with others, some did volunteer that they found conferences a good place for "talking to people over a beer and opening up," for example.

Twelve of the respondents spoke of teaming, connecting, or engaging with others within Sandia, while ten spoke of teams that crossed institutional boundaries with universities, other national laboratories, or industry. Some in these two sets overlapped. One respondent said that she would try "either another lab or university if I can't find someone at Sandia," while another was more parochial, stating that "I find that I can almost always find experts in whatever I am interested in right here at Sandia (either New Mexico or California)." Of those who did work with other institutions, four spoke of the (bureaucratic) difficulties and barriers to doing so.

Some of the respondents were quite explicit about the need to continually engage with new/different individuals. "People get in a rut with what they know and who they work with," said one, describing an environment defined by strong ties. Another pointed out that "innovation often comes from someone familiar but a little outside." One respondent said that her "willingness and

[5] The strength/weakness of a tie per Granovetter (1973) is measured by "a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding) and the reciprocal serves which characterize the tie" (p.1361). In a research or invention environment, weak ties might be connections an individual develops with colleagues she meets once a year at a physical conference, and with whom she has in common only an interest in a particular domain and an annual presence at the conference.

openness to interact with people I don't know" was critical to her success in cross-domain work. Three respondents spoke of their "bridging" role on a team with multiple disciplines.

3.4. What Do the Teams Look Like?

Team-based research poses difficulties of its own. Respondents indicated that they were aware of those difficulties and willing to face them as the nature of the work required multiple perspectives.

3.4.1. Team Characteristics

An assumption expressed by many of the respondents was that interdisciplinary collaboration was inherently valuable and required a team to execute. "Today [we use a] much more interdisciplinary approach…not [a] single investigator. [We] need different backgrounds," said one respondent, implying that the disciplines were each represented by a different individual. Interviewees repeatedly stressed the nature of team characteristics as an important factor in cross-disciplinary collaboration. Key themes that arose under this topic were the following:

- Degree of *multidisciplinary* collaboration—where each team member's unique domain knowledge complements the others, but team members have little depth of knowledge in domains other than that which they were formally educated.
- Degree of *interdisciplinary* collaboration—where team members have a greater depth of understanding of technical domains in which they were not formally educated.
- Nature of interpersonal relationships with one's team members—characterized by the presence or absence of trust, mutual respect, and empathy among team members.
- Physical operation of the team—physically co-located; separated, collaborating via phone and internet; and gradients between these two modes

Fourteen respondents, or over half the sample, stressed the importance of the degree of interdisciplinary efforts in their work. Example comments include: "See[ing] synergies between what you can do and what others can do…[helps you] build ideas," "I also work on teams: physicists, chemists and computer scientists. They are all over the place in terms of specialist knowledge," and "I build wide-ranging teams and try to bridge the gaps between them. The background work on principles is essential for understanding how to build the right team. I will usually try to include someone on each team who has a technical perspective that's unique to the problem—like involving a biologist on a mechanical engineering project. The diversity of perspectives helps reveal new approaches to the problem."

On the depth of collaboration, one respondent noted that there is "consistent cross-disciplinary collaboration. With more background in other areas I can inform the chemistry and I also get additional perspectives/opinions," and another pointed out that "It's when you struggle, and when you are collaborating with someone, struggling together to figure out what things mean. That's where the real innovation comes." There was a palpable sense from these respondents that deeper levels of cross-domain interactions led to productive outcomes than would a team environment in which one individual was responsible for weaving together the threads from separate participants.

Twelve individuals commented on the importance of trust among team members and of interpersonal dynamics. Respondent comments on trust included, "[You] have to build comfortable networks [so that you] can ask stupid questions of people who you trust...that is hard to force when you don't know the people," "[I] want to be on your team because I like the dynamics and way to

approach problems and research," and "Projects where each contributor does his own part don't advance knowledge deeply."

There were a range of perspectives on the most effective ways for interdisciplinary team members to interact. Some were emphatic that the connection was inherently personal and required face-to-face interaction: "[It's] all about interpersonal interactions. [It's] NOT done over internet" (emphasis by the respondent). Others were much more comfortable with online meetings, although respondents in this camp still emphasized the importance of the human connection. "We make it a habit to get together once a week. These are mostly online meetings. It is important to keep up contacts."

3.4.2. Communication

Analysis of the interview data showed that nineteen respondents underlined the importance of communication as a critical factor for the success of combinatorial collaborations. This concept was commonly framed as an initial problem, then strategies were presented for how collaborators typically overcame communication issues. Respondents initially cited a necessity to communicate aspects of their research at a level that was accessible to individuals outside their field. However, some respondents noted that the greater familiarity collaborators had with each other's technical disciplines, the better the chances that collaborations would find themselves defining and solving new problems. For example, respondents mentioned that to "get interdisciplinary teams to common language depends on how diverse they are" and that "You have to break through the jargon and really understand the concepts, otherwise you can misconstrue a problem:" One respondent gave a description of paradigmatic differences between disciplines:

> "It's almost like you are working on the same problem as other folks, but your approaches and vocabularies are different, so you have a feeling it's worth sharing and learning. For example, physicists have almost resigned themselves to not being able to deal with large systems, so they pick some small piece...that can inform the larger piece. Chemists are willing to look at the larger piece all at once, and you learn different things by doing that."

3.4.3. External Networks

Many respondents spoke to the importance of connections with individuals outside of Sandia and the dynamics of cooperation and competition. Seven respondents indicated that external networks were important to their work. "Networks and contacts [both inside and outside Sandia] are important," according to one respondent. Thirteen respondents commented on the need for cooperation. The comments spanned topics such as the need for diversity in problem solving, the identification of collaborators and team members, and how to operationally accomplish putting together an external collaboration. For example, one noted that "in terms of external collaborations, if I were to give advice, it'd be to keep your connections with good people, even if there isn't an immediate project you can work on with them."

These responses about cooperation are connected to the question of Sandia's influence and reputation, which factors into the ability of Sandia researcher to attract the interests of external collaborators. There was a general belief among respondents that Sandia has a good reputation in certain areas, which gives researchers credibility when establishing external research collaborations. "Having a Sandia business card opens doors," said one respondent.

3.4.4. Risk of Failure

In response to direct questioning about failures, seventeen, or over two-thirds of the respondents reframed their failures as a critical part of the scientific enterprise. As respondents put it, "you have to fail to learn," and "[failure]…is where you get your best stuff." Others pointed out that "Being open-minded to new goals, not to mention learning, means that you really don't fail." Yet another said that "I need to make as many mistakes as I can so I can flesh out the path towards the right thing." The respondents were adept at finding value throughout their work. "Of course, you can't do what you promised. But you can always get intermediate milestones or learnings that you can…[call] success." It should be noted that there was considerable emphasis placed by all respondents on the need for strong communication about the objectives and limitations of research as far as sponsoring entities are concerned. However, it was quite striking that so many reframed the question from one of risk to one of progress: "[Failure] is the nature of research, at least for me. Maybe one wouldn't call it failure, though."

While failure was reframed as a positive experience, external competition was seen as a pressure. It was a reoccurring theme in thirteen interviews. "Everything is a competition," said one, "…to see who can get papers out first." However, while talk of competition addressed private industry and universities, there was not much talk of competition among U.S. national laboratories.

3.5. What about the Organization in which Researchers Are Embedded?

The study team asked questions about the barriers and incentives in pursuing combinatorial research as well as the one thing Sandia could change to encourage combinatorial research. The grounded analytic approach to the responses clearly identified several categories under the overarching topic of Sandia influence (on them or their work) into which respondent comments fell.

Four respondents viewed Sandia as neutral towards their self-cultivation of a combinatorial capacity. For example, one respondent said that "Center X could easily devalue what I'm doing, because I'm not feeding directly into our mainstream Science Campaign goals. But it doesn't." Or, in another example, "I'm stubborn, so even through many lean years of funding I persisted [with my combinatorial work] and now I've been pretty successful." Another respondent pointed out that "I have come to the realization that I won't receive the level of recognition here [at Sandia] that I would in industry. I'm not optimistic about becoming a D [the top personnel category for researchers] because I'm not—I'm not narrow enough." Note that although she would not get promoted, she also was not stopped from or penalized for working on her own combinatorial agendas.

Examples of Sandia's agnostic stance towards the development of an institutional capacity for combinatorial research focused on hiring. Ten respondents viewed Sandia as basing its hiring practices on criteria other than the presence of (or the potential for) a combinatorial capacity. "We aren't getting the crazy ideas. We stopped hiring that kind of person," said one. Respondents spoke of Sandia's ability to recruit and retain top talent, while simultaneously noting the Labs' inability to lead in open literature and publications in key areas: "The focus on quantum information science, optics, etc. at Sandia has degraded. Publications have gone down. We have concentrated for so long on projects and deliverables." Another pointed out that "there are several areas where we are below critical mass [in terms of the number or quality of researchers]—we've lost the race in several research areas because of our own doing." Respondents saw the failure to hire individuals with combinatorial capacity as a (perhaps unintended) consequence of a focus on other criteria, rather than of a deliberate decision.

Information control regimes such as security-related classification restrictions can have a significant negative impact on the quality of work and so on the attraction of Sandia to top-level talent. By definition, security classification does not allow certain types of Sandia's work to be subjected to the control systems of the scientific community, such as peer review, which can weed out bad ideas. "Classification makes it very easy to hide bad science," said one. Another commented that "sometime people hide [bad] work behind classification."

None of the respondents felt that Sandia actively encouraged or discouraged the development of combinatorial research agendas. However, eleven respondents, or almost half of the respondent pool, felt that the Labs often chose paths or directions that worked against the non-traditional research areas and unusual findings allowed by cross-domain research: "Sandia's LDRD process[6] will reject things innovative and cutting edge," said one. Another noted that "Innovation [at Sandia] requires subterfuge, entrepreneurship, and the willingness to do it off core hours." Ten of the respondents explicitly noted that work on the types of projects the interview discussed had to be done off-hours, on one's own time, characterizing that commitment to off-hours time variously as a challenge to be met or a sacrifice that must be made. As one respondent said in a quote given earlier, "the problem there is that there's little time for the rest of life."

Although no respondents felt that Sandia actively *discouraged cross-disciplinary* research, ten respondents felt that Sandia actively *encouraged disciplinary* work. By and large, that encouragement took the form of Sandia's focus on short-term customer needs and how that focus translated into the transactional project/task system by which Sandia allocates time and work. "I see Sandia getting further away from research," said one respondent. "You just apply what's there, so you can do it quickly." Another respondent said that "[I am] always worried about losing money so [I am] always chasing money," said one respondent. Another pointed out that "Down on the ground…what researchers really care about and protect is who is filling my timecard today." "It's not OK not to have funding," said another. "I might not get fired, but the expectation is that I will cover myself financially," As a consequence, "[researchers] will make sure the customer who is paying them is happy." And finally, respondents took the thread to its conclusion. "To be successful as a researcher at Sandia you have to be deep, because deep is what brings in dollars." Another respondent pointed out that she felt that "The biggest impediment [to the ability to practice combinatorial research] is Sandia's timecard mentality. It totally limits innovation. The nature and fragmentation of funding is also a huge problem." And as was mentioned in an earlier section, "It is the lack of elasticity at Sandia [fostered by the full cost recovery model] that makes things difficult. You can't just ask someone to help with something…because [by definition] they are already fully funded (or even oversubscribed)."

Several respondents spoke to the encouragement or discouragement by Sandia of "collisions" and intermixing of ideas among colleagues and potential colleagues, as they felt this was a critical way to stimulate innovative ideas. Respondents were balanced in their view of whether Sandia encourages or discourages these collisions.

Nine respondents noted that Sandia does encourage such collisions, with comments such as: "[Our] engineering and science lab…has everything. Constant tumble of people bumping into each other from other areas." And "I find that I can almost always find experts in whatever I am interested in right here at Sandia (either in New Mexico or California)."

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[6] The only discretionary funds available to Sandia are Laboratory Directed Research and Development (LDRD) funds which are distributed to staff in the form of projects. The process is a competitive one. Competitions are usually held among proposals addressing similar problem spaces defined *a priori* by Sandia leadership.

On the other hand, thirteen respondents commented that Sandia does discourage this type of collision among ideas. "It's…a matter of social interaction within Sandia," said one, "which doesn't happen very much." When asked if Sandia could do one thing to stimulate combinatoric agendas, one respondent said "free-form interaction not encumbered by accounting for every minute of one's time." Several respondents mentioned security information control (including but not limited to classification) as a means by which idea collisions, particularly with the external scientific community, are discouraged: "Looking for interactions with people outside of Sandia is more problematic. I never quite know what I can talk about or not."

Aside from security information control, the project/task charging system and its lack of flexibility to accommodate idea collisions that are of more long-term than short-term benefit were mentioned. Again, the lack of elasticity required by the full cost recovery model came in to play. "You can't just ask someone to help with something…because they are already fully funded (or even oversubscribed)." Others felt that the task focus of the Labs worked against idea collisions. "Generally, I feel like we have a culture where getting work done rather than finding out what the person next door is doing is more valued." Another pointed out a well-known model: "It's also a matter of social interaction within Sandia—which doesn't happen very much. For example, at the Santa Fe Institute, there would be a free tea hour every day at the group or building level."

4. SUMMARY AND DISCUSSION

The study team used a snowball sampling technique for the ethnographic data collection portion of this study. While there are questions about the completeness of the sample (at twenty-five individuals, it is 0.004% of Sandia's approximately 7,000 research and development staff), it did meet face validity for members of the study team with a high-level perspective on the Labs' research and development efforts. If there were individuals who were missed, it was on the order of tens of individuals—a sample that would still be a very low percentage of the total population of interest. Furthermore, the responses from this particular sample showed enough similarity across the sample and conformance with expectations from various bodies of study on combinatorial research and research agendas in general that the results have validity.

For the respondents, complex problems, foresight, and analogic thinking drove the cross-domain approaches found in combinatorial research. Structurally there are both incentives and barriers to pursuing this research. On the incentive side, respondents identified the following: surprising solutions grab the attention of funding bodies, working in the gaps decreases competition, and there is potential for increased return on investment. On the barrier side, respondents noted that obtaining funding for an idea was required and that there is a large intellectual risk in moving into domains where one is not formally trained. All respondents saw the need for combinatorial research.

The growing corpus of knowledge that can be used to address complex problems is becoming ever more accessible to the individual researcher with the desktop (fingertip) presence of sophisticated search engines, various mechanisms of information push such as listserv, and the increasing number of black box algorithms that make it easier for an individual researcher to cross domains. A tension has arisen between what can be learned (the accessible corpus of knowledge) and the slow "hard work" of learning (e.g., reading, conference attendance, personal interaction, and development of craft). Combinatorial researchers at Sandia were making use of new learning tools (e.g., data mining via machine learning, black box algorithms, etc.) in their learning strategies to some degree but these tools could be embraced more fully. The rise of serendipitous exposure to a variety of domains through these technological advancements, however, was central to developing combinatorial research agendas for the respondents. As noted by Loreto et al. (2016), the size of the base constituent space forms the combinatorial capacity for new research, and for the respondents' 'luck' is central to connecting dots between domains. The interviews and the associated literature drew a picture of an individual type that would be most likely to engage in combinatoric research. The type is described by both demographic and psychographic components.

The results of this study generally support several strands in the research on combinatorial research around the question of the individual type. The type tends to be mid- or late-career with a well-established reputation in some discipline. The combinatorial researcher also is characterized both by skill and by disposition. She exhibits deep disciplinary knowledge and reputation, in addition to the contributions she makes to combinatorial agendas. She has personality characteristics, such as extraversion and agreeableness that suit her well for teamwork, while retaining the discipline and search for order that suit her well for disciplinary work. Her empathy and curiosity open her to the possibilities of other perspectives and stimulate an interest in learning them.

The organizational environment within which respondents worked (Sandia) was agnostic toward combinatorial work. Skills-based hiring practices that favor deep domain knowledge and time reporting requirements that limit curiosity driven exploration were the two most frequently mentioned organizational dynamics underlying the pursuit of combinatorial research. Projects at Sandia, a science-based engineering laboratory, are frequently focused on a deliverable to meet a

customer's pre-defined, relatively near-term need. Historically, those projects have required deep domain knowledge, not broad perspectives that integrate multiple domains. Using skills-based hiring, Sandia focused on ensuring that the needs of current projects were met. Whole person hiring, which would recruit researchers interested in exploring and defining new problem spaces, is not used. So, while Sandia does not explicitly discourage combinatorial work, it does not actively seek researchers who are both interested in it and capable of performing it. The timecard culture, which is a function (to some large degree) of the full cost recovery business model used at Sandia, requires that *all* of a researcher's time be accounted for by customer-paid projects or management-generated administrative cases. Hence, a researcher must first and foremost ensure that she is fully funded, which will normally imply that she is working on tightly constrained projects. Therefore, much of the exploratory work and learning must take place on a researcher's own time—evenings and weekends. This aspect of organizational culture leaves no place for the informal, unstructured intellectual conversations that respondents felt were necessary to produce combinatorial research agendas.

Late-career respondents (defined as those with twenty or more years of professional experience) comprised close to half (40%) of the sample for this study, despite specific requests to respondents for names of early-career individuals while the snowball sample was being built. Respondents did feel that the intellectual capital they had accumulated through the early and perhaps middle portions of their career was a key resource allowing them to engage with combinatorial research agendas (see also Azoulay et al [2018] who make a similar argument for entrepreneurs).

The accumulated intellectual capital mitigated the risks of combinatorial work for the respondents. Combinatorial work can be more risky than deep disciplinary work for the individual as combinatorial researchers tend to publish less than disciplinary researchers. When they do publish, the publications on combinatorial work are likely to have either few citations or make a significant impact—unlike disciplinary work which falls in the middle of those two extremes (Leahey et al, 2017; Abramo et al, 2019; Foster et al, 2015). Respondents in this study believed that their already developed reputational success provided them confidence as they moved as neophytes into new areas with combinatoric work. That success reduced the perceived intellectual and associated reputational and career risk associated with combinatoric (vs. deep disciplinary) research.

Bateman and Hess (2015) argued that depth-seeking behaviors in researchers were correlated to high scores on the Big Five personality characteristic of conscientiousness, and breadth-seeking behaviors to a high score on openness to experience. Respondents in this study described behaviors and attitudes related to cross-domain work with language that correlated to descriptors of the openness trait, e.g., open to learning, curious, and being comfortable with some level of discomfort. However, the same set of respondents also provided descriptors that corresponded more to the conscientiousness trait, such as references to the importance of "doing homework" or the various costs of being intellectually agile. The researchers' language suggested that they always are managing a tension between these two dimensions, rather than falling completely into one or the other category. This observation is supported by Bateman and Hess's (2015) study.

The concept of a T-shaped employee captures the ability to exercise both breadth and depth. This concept has most visibly—and influentially—been used at McKinsey & Company, Apple, and the design firm, IDEO (Bartlett, 2006; Hansen, 2010; Gino, 2018; Jackson, 2019). The downstroke of the T represents disciplinary depth and the cross-stroke represents personality characteristics such as curiosity and openness to new experiences, which can translate into disciplinary breadth.

Since most combinatorial work is done on teams (Wuchty et al, 2007; Falk-Krzesinski et al, 2010; Fiore, 2008), researchers also must be good team players. Interestingly, interview responses contained very few references to intellectual capability and the importance of intelligence, and many comments related to the researcher's ability to function well in a team environment.

The combinatorial teams that respondents formed or participated on were constructed through their presence in social networks, often formed through presence at conferences or other professional contacts. It is important to note that their ties to colleagues in these networks are what Granovetter (1973) would call "weak ties"—rarely activated and characterized by low levels of affect. However, as Granovetter (1973) and Rogers (1983 [1962]) before him would persuasively argue, it is through weak ties that individuals most often get new ideas or different kinds of information, making those ties ideally suited for the types of idea collisions that often generate new spaces for investigation and research.

One of the triggers for the creation and development of combinatorial research agendas among the sample seems to be a recognition that the important target problems were engaging multiple and quite different perspectives. Questions about using 3-D printing for battlefield weapons, for example, might involve disciplines as divergent as materials science, data analytics and advanced computer modeling techniques as well as military experts and those involved with logistics. The amount and diversity of knowledge in each of those fields precludes the possibility of a polymath, fully conversant in them all. According to respondents, study teams consisting of T-shaped individuals with deep domain knowledge in one or more relevant areas and the curiosity required to engage with other, new (to them) areas are required to execute these agendas.

5. CONCLUSIONS

According to the interviews, participants felt that Sandia today is structured to engage primarily in transactional relationships with customers with relatively short time horizons. The types of projects on which Sandia works generally require deep disciplinary knowledge. Sandia as an organization, as perceived by the respondents and in which they worked, sets up a tension for the combinatorial researcher. While Sandia was generally agnostic towards combinatorial research, that agnostic posture depended on whether the researcher was able to fulfill all her customer obligations.

The analysis of the interview data by the study team raised several possibilities for follow-on work. The methods questions around sampling and associated issues of representativeness will need to be addressed. Psychometric studies on the incidence of various personality traits and characteristics that distinguish the combinatorial researcher from researchers doing deep domain work would be useful. A longitudinal study of researchers at a given institution would show whether there would be a fall-off in face-to-face connections as a generational cohort more comfortable with electronic information-related tools comes of age. A comparative study of an organization that hires for research breadth, yet had staff working in (and/or migrating to?) areas that focused heavily on deep domain knowledge could be interesting. Finally, a rigorous network study of the formation of multi-domain teams, both within a large organization like Sandia (or a university) and across institutions (a national laboratory and a university, for example) could be quite enlightening.

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APPENDIX A. INTERVIEW PROTOCOL

- We believe that the **way R&D is being conducted is changing** and lots of innovations that are concerning for national security are arising out of this new way.
- We are interested in exploring whether or not there are **differences in the processes of innovating** that can be used to selectively direct towards particular **types of innovation outcomes**.
- We think that there is a *growing base* both here at Sandia and externally of accumulated knowledge, both in terms of phenomena (explanations of nature/often called "science") and in technologies (the embodiment of a use of a phenomenon for a purpose) across all domains.
- We think that this compendium of ideas is both ***becoming larger in size*** and becoming ***easier to access.*** As such, it has allowed a ***combinatorial approach*** to innovation to be easier and more fruitful.
    - Examples with national security implications: information storage in biological systems, "platform technologies": drones with XX added (cameras, weapons, etc.), satellites with XX added, self-healing materials (on weapons for instance) …
- Sandia may or may not be encouraging us to participate in this new way.
- Here b/c we think you *might* be using this new R&D method.
- Today we want your feedback on where we are right/wrong and how we can better improve our understanding based on your experience.
- We are going to keep our written notes unclassified. However, we are all Q-cleared, so if there is something classified you think would be helpful, please flag it. We can talk about it, but we do not want to take notes on it
- Before we go there – I would like to get some background on you
    - **How long** have you been at the labs?
    - Primary area of expertise? Have you switched areas during your career?
    - What **percent of your time** do you spend on research?
- Do you *assimilate or combine ideas* from multiple domains in your research? Can you give us an example? (probing for phenomena or technologies)
    - How do you **learn about ideas outside your direct area of expertise** to use in research?
- **How far out of your direct area of expertise** do you go? (diversity and degree of incorporation)
    - Does classification/compartmentalization impact distance?
- How do you incorporate these ideas into your work? e.g., do you get smart in these areas yourself, get collaborators …?
    - If respondent uses collaborators - How do you pursue these collaborations?
- What personal characteristics do you feel a researcher needs to be good at these types of research?
    - Allow a response, then probe: pace of research?
    - Failure rates?
    - Often results from these types of research are counter-intuitive or surprising. How do you handle that type of reaction?

- Are there risks if we do not pursue this type of research? If so, what are they?
- Are there particular domains where it is more important than others? Which ones?
- What, if any, barriers do you feel SNL has in place preventing staff from working in these modes? How about incentives?
- Lessons learned?
- If there were one thing Sandia could change to create a research environment more conducive to these types of research, what would it be?

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